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Progress has been made in six areas. First, a task battery to assess high-level visual abilities has been fully implemented. This battery is administered and scored on the Macintosh computer. Second, the task battery has been used to examine one patient in detail, and has diagnosed a subtle visual deficit that is consistent with both the lesion location and regions of hypometabolism (as measured by PET scanning). Third, additional brain-damaged patients have been tested in order to discover whether the visual angle subtended by imaged objects is systematically related to the amount of damage to the occipital lobe. Data from these three patients suggests such a relation. Fourth, the computer simulation of high-level vision is fully functional, and predictions have been generated about previously unnoticed syndromes. For example, the model predicts that some patients will be able to recognize faces but not common objects. Some of these predictions currently are being tested. Fifth, three (continued)


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subjects have been given imagery tasks while being PET scanned. The results are consistent with the predictions of the theory. In particular, the medial occipital and frontal activation is consistent with the claim that images are patterns of activation in topographically mapped areas and that they are built up sequentially. Finally, response time studies using divided visual field techniques have provided evidence for two ways of representing spatial relations, as categories (e.g., left/right; above/below) or precise metric amounts; the left hemisphere is generally more effective at computing categorical spatial relations, and the right hemisphere is generally more effective at computing metric spatial relations. Additional experiments have provided evidence that both types of spatial relations can be used to arrange parts into a visual mental image.

AFOSR-TR- 89-1733

# Annual Technical Report

"The Neuropsychology of Imagery Processing" (88-0012)

S. M. Kosslyn, PI

December 1989

## Research Objectives

### General objectives

The research has two general objectives:

1. To characterize further the nature of the processing subsystems used in imagery.

2. To discover the realization of specific processing subsystems in the two hemispheres of the brain.

### Specific objectives

To accomplish these goals, there are four specific objectives:

1. Develop a comprehensive task battery
Numerous tasks are required to garner evidence for distinct subsystems. The theory developed in our laboratory has guided us to develop a set of tasks which, when the results are taken together, should allow us to determine whether brain damage has selectively affected individual subsystems.

2. Test brain-damaged subjects
Brain damage can selectively affect specific aspects of processing. Thus, we plan to test a range of patients who have selective deficits. We have just begun this aspect of the research, which waited on our implementing the task battery.

3. Computer simulation models
The effects of brain damage on behavior are complex. In order to generate predictions precisely, we needed to implement a computer simulation model. The model is running, and has produced a number of specific predictions.

A-1

4. Divided visual field studies with normal subjects

Both of the general objectives are served by divided visual field studies of normal subjects. To the extent that there is a dissociation between field and task, one has evidence for distinct processing subsystems. And the nature of the dissociation informs us as to how processing is implemented in the hemispheres.

## Status of the Research

Progress in achieving these objectives has been made in six ways.

1. Task battery

A task battery to assess high-level visual abilities has been fully implemented.

*Theoretical underpinings*. Neurophysiological and neuroanatomical studies of nonhuman primates have documented that there are two major cortical pathways used in identifying objects visually. One is concerned with processing *what* an object (or part) is, whereas the other is concerned with processing *where* it is. The pathway concerned with recognizing shape runs from the occipital lobe down to the inferior temporal lobe, whereas the pathway concerned with location runs from the occipital lobe up to the parietal lobe.

These two visual pathways must converge at an *associative memory*, where the two kinds of information are integrated. Associative memory plays several critical roles in allowing one to exercise visual-spatial abilities, including helping to guide attention to critical details of a viewed object. Although the memories themselves appear to be stored in various places throughout the brain, structures in the frontal lobe have been shown to be critically involved in actively seeking out information stored in memory.

Finally, one can *manipulate* stored visual information in various ways in the course of reasoning visually. This kind of activity requires one to activate stored visual information and then to transform it, observing the consequences of such mental manipulations. The frontal and parietal lobes play critical roles in such processes.

Structure of the battery. The battery is designed around a decision tree. Subjects are first tested on four tasks. If there is a deficit on the first task, one or more component processes used in the temporal lobe shape-identification system is awry; if there is a deficit on the second task, one or more component processes used in the parietal lobe location system is awry; if there is a deficit on the third task, one or more component processes used in accessing stored information to direct attention or to form images is awry; and if there is a deficit in the fourth task, one or more component process used to manipulate stored visual information and observe the consequences is awry. Once scores from these four "screening" tasks are examined, the relevant branches of the tree are descended, as briefly described below.

*Processes that recognize shape.* A deficit in recognizing shape could reflect a number of distinct underlying deficits. The battery allows one to determine whether the deficit is due to a problem in adjusting attention to the size of the shape, in scanning the shape, in extracting key features of the shape, in storing an initial shape, or in matching a perceived shape to a stored shape.

*Processes that specify location.* A deficit in specifying location also could be due to a number of dysfunctions. The battery allows one to determine whether the problem is in registering two objects at once, in specifying location relative to objects rather than the retina, in encoding metric information, or in encoding "categorical" information (e.g., left/right; above/below).

*Processes that look up stored information.* A deficit in directing one's attention to the appropriate locations or in forming mental images could be due to processes that look up information stored in memory or to processes that use this information. The battery allows one to assess both types of potential deficits.

*Processes that manipulate stored information.* A deficit in mentally manipulating visual information could reflect a deficit in being able to retain visual information in mental images, imagine a pattern being transformed, or interpret the consequences of a mental transformation. The battery allows one to assess these types of potential deficits.

Use of modern chronometric techniques. A score on most tests reflects the efficacy of all of the component processes that must be used to perform the test. Thus, such scores are inherently ambiguous; they could reflect a set of rather general factors, such as speed of processing or of responding, as well as the specific factors they are designed to index. This problem with most currently available tests is widely acknowledged, but little has been done previously to address it. The present battery is based on a different approach, derived from the work on "additive factors" in cognitive psychology. This work hinges on the observation that specific variables can be identified with specific stages of processing; thus, by varying the value of the variable, one can selectively tax a specific stage. The present battery is based on this idea; we include at least three levels of a key variable within each test, and the score is a measure of increased difficulty over these levels. This technique allows us to assess the efficacy of specific component visual-spatial processes.

*Administering and scoring the battery*. The battery is implemented on a standard Macintosh Plus or Macintosh SE computer. The computer presents all instructions and stimuli, and it records responses, errors, and response times. At the end of each test the computer prints out two scores, one based on response times and one based on error rates. (A third score, combining the two, is easily computed and will be available in the final version.) The scores are then compared against normative scores, and a deficit is defined as a test score that falls outside the .05 confidence interval of the normal scores. The entire battery, should it be necessary to administer, requires about 3 hours for an otherwise healthy brain-damaged subject. The four screening tasks require about 20 minutes to administer, and it is almost never necessary to administer the complete battery after the scores on the screening tasks are seen.

2. Using the battery to test brain-damaged patients

The task battery has been used to examine one patient in detail, and has diagnosed a subtle visual deficit that is consistent with both the lesion location and regions of hypometabolism (as assessed by PET scanning). The patient displayed only a mild deficit in naming pictures (he was incorrect on 13% of the trials). This patient is unusual insofar as he has Broca's aphasia with no sign of a cortical lesion on CT scan; however, there is evidence of damage to white matter (the head of the left caudate) and of hypometabolism in both the left frontal lobe and occipito-temporal area. Thus, it was of interest to discover that he has selective deficits for image rotation and generation (both of which are posited by our theory to recruit processes implemented in the frontal lobe), but not for image scanning (which putatively does not require those structures). We also have preliminary evidence that he has difficult extracting "nonaccidental features" during perception. We are now in the process of analyzing his results in detail and comparing them to those from age- and education-matched control subjects. We have established a good mechanism for recruiting additional patients at the Massachusets General Hospital, and have other patients scheduled to be tested.

3. Additional patient testing

We have tested three additional brain-damaged patients on a task designed to assess the contribution of the occipital lobe to visual imagery. These subjects have varying amounts of damage to the occipital lobe (as well as to other structures, unfortunately). The task required subjects to decide from memory whether a named object is higher than it is wide; the objects were selected so that this discrimination is relatively subtle, and imagery typically is reported to be used. Subjects are seated in front of a blank white screen, and are asked to "project" their images of the objects on the screen in front of them when performing the task. Immediately after each item, the subject is asked to point to where the leftmost side of the object would be and where the rightmost side of the object would be if a picture of the object had been projected on the screen as it appeared in the image. A compass is mounted under the subject's chin, and all pointing is done with a pointer mounted on the compass. Thus, we could read off both the angle subtended by the imaged object and whether the object was located directly in front of the subject. It is of interest that all three subjects with occipital lobe damage show visual angles at least half those of normal control subjects (when we correct for bias in pointing). In contrast, subjects with parietal lobe damage or subcortical (thalamic) damage that affects vision do not exhibit smaller angles. Furthermore, we discovered that one of these control subjects (who had damage to his left LGN) observed imaged objects drifting into his blind field; this result allows us to speak against the role of "tacit knowledge" of perception in producing the results, given that the subject never actually sees anything in his blind field. Thus, the evidence collected thus far is consisient with the claim that images are spatial representations the are supported by structures in the occipital lobe.

4. Computer simulation

The computer simulation model was described in last year's annual report. We have used the program to generate a series of predictions, which are being published in the next issue of Cognition. We are actively seeking patients who show deficits that are consistent or inconsistent with predictions. For example, the model predicts that some patients will be able to recognize faces but not common objects. It also predicts that some subjects who have difficulty recognizing faces will also have difficulty recognizing objects seen from unusual points of view.

5. PET scanning

This work was not anticipated in the original proposal. However, we were invited to collaborate with the PET group at MGH, and have begun to make exciting discoveries using this technique. So far, three subjects have been given imagery tasks while being PET scanned at the MGH (this work is in collaboration with Dr. Nat Alpert, who obtained the necessary approval of the human subjects committee at the MGH). The results are consistent with the predictions of the theory. In particular, the medial occipital and frontal activation is consistent with the claim that images are patterns of activation in topographically mapped areas and that they are built up sequentially. In addition, we have begun a collaboration with the Washington University PET scanning group, and plan a study to examine the precise correspondences in activated brain areas in imagery and perception. The study is designed to allow us to examine directly the effects of spatial properties of imaged patterns on the patterns of activation in the brain (particularly in areas in extrastriate cortex that are known to be topographically mapped in nonhuman primates).

6. <u>Response-time experiments with normal subjects</u>

Finally, response time studies using divided visual field techniques have provided evidence for two ways of representing spatial relations, as categories (e.g., left/right; above/below) or precise metric amounts; the left hemisphere is generally more effective at computing categorical spatial relations, and the right hemisphere is generally more effective at computing metric spatial relations. Additional experiments have provided evidence that both types of spatial relations can be used to arrange parts into a visual mental image.

In addition to these studies, we have continued to develop the theory by conducting experiments with normal subjects. Perhaps the most intriguing result (obtained in collaboration with C. Cave) focused on the time to identify line drawings of familiar objects. The drawings were presented completely intact, with the parts separated slightly but their spatial relations maintained, with the parts separated and presented in incorrect locations, with the object segmented arbitrarily but these segments being in the proper spatial relations, or with the object segmented arbitrarily and presented in incorrect locations. (Part boundaries were determined by having a separate group of subjects indicate segments, as was done by Biederman; we, as did he, found high agreement among these subjects.) The interesting prediction hinges on a distinction between Lowe's theory of object encoding and Biederman's theory. Lowe claims that "nonaccidental properties" (parallel lines, points of intersection, etc.) are extracted, and then the set is used to index a stored model; this indexing process operates with the constraint that the nonaccidental properties must be consistent with seeing a single object from a single point of view (the so-called viewpoint consistency constraint). On this theory, the critical variable should be disruptions of the viewpoint consistency constraint, and hence scrambling the spatial relations should disrupt naming time. In contrast, there is no reason to think that it is important whether the object is broken along part boundaries or is borken up arbitrarily. On the other hand, Biederman's theory stresses the recovery of "geons" during encoding (geometric shape primitives), which should be disrupted when the parts are segmented arbitrarily. Thus, it is of real interest that naming times were significantly impaired when parts were scrambled, but there was no effect of how the object was broken up. This finding has been replicated, and another variant is currently being conducted.

## Publications During Grant Period

Kosslyn, S. M., Sokolov, M. A., and Chen, J. C. (1989). The lateralization of BRIAN: A computational theory and model of visual hemispheric specialization. In D. Klahr and K. Kotovsky (Eds.), *Complex Information Processing Comes of Age*. Hillsdale, NJ: Erlbaum.

Kosslyn, S. M. (1989). Imagery. In D. Osherson, S. M. Kosslyn, and J. Hollerbach (Eds.), *An Invitation to Cognitive Science*. Cambridge, MA: MIT Press.

Osherson, D., Kosslyn, S. M., and Hollerbach, J. (Eds.) (1989), *An Invitation to Cognitive Science*. Cambridge, MA: MIT Press.

Cave, K. R., and Kosslyn, S. M. (1989). Varieties of size-scaling in attention. *Journal of Experimental Psychology: General., 118*, 148-164.

Kosslyn, S. M. (1989). The psychology of visual displays. *Investigative Radiology, 24*, 417-418.

Rueckl, J. G., Cave, K. R., and Kosslyn, S. M. (1989). Why are "what" and "where" processed by separate cortical visual systems? A computational investigation. *Journal of Cognitive Neuroscience, 1*, 171-186.

Kosslyn, S. M. (1989). Understanding charts and graphs. *Applied Cognitive Psychology. 3*, 185-225.

Van Kleeck, M. H., and Kosslyn, S. M. (1989). Gestalt laws of perceptual organization in an embedded figures task: Evidence for hemispheric specialization. *Neuropsychologia*, 27, 1179-1186.

Holtzman, J. D., and Kosslyn, S. M. (in press). Components of mental imagery: Neuropsychological evidence. In A. Caramazza (Ed.), *Advances in Cognitive Neuropsychology*. Hillsdale, NJ: Erlbaum.

Kosslyn, S. M. (in press). Computational theories of imagery. *Dictionary of Cognitive Science*. London: Basil Blackwell.

Kosslyn, S. M., and Van Kleeck, M. (in press). Broken brains and normal minds: Why humpty-dumpty needs a skeleton. In E. Schwartz (Ed.), *Computational Neuroscience*. Cambridge, MA: MIT Press.

Kosslyn, S. M., Cave, C. B, Arditis, A., and Gabrieli, J. D. E. (in press). Visual imagery in the blind side: a neuropsychological test of the tacit knowledge hypothesis. *Brain and Cognition*

Kosslyn, S. M., Flynn, R. A., and Amsterdam, J. B. (in press). Components of high-level vision: A cognitive neuroscience analysis and accounts of neurological syndromes. *Cognition*

Kosslyn, S. M., Van Kleeck, M. C., and Kirby, K. N. (in press). A neurologically plausible theory of individual differences in visual mental imagery. In J. T. E. Richardson, P. Hampson, and D. Marks (Eds.), *Advances in Mental Imagery*. London: Routeledge.

Kosslyn, S. M., Segar, C., Pani, J., and Hillger, L. A. (in press). When is imagery used? A diary study. *Journal of Mental Imagery.*

Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., and Gabrieli, J. D. E. (in press). Evidence for two types of spatial representations: hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception and Peformance*

Van Kleeck, M. H., and Kosslyn, S. M. (in press). The use of computer models in the study of cerebral lateralization. In F. L. Kitterle (Ed.), *Cerebral Laterality: Theory and Research.* Hillsdale, NJ: Erlbaum

Kosslyn, S. M., and Chabris, C. F. (in press). Naming pictures. *Journal of Visual Languages and Computing*,

Kosslyn, S. M., Margolis, J. A., Barrett, A. M., Goldknopf, E. J., and Daly, P. (in press). Age differences in imagery abilities. *Child Development*,

Kosslyn, S. M., and Park, S. (in press). Hemispheric differences in memory for lateral orientation. *Brain and Cognition*,

## Participating Professionals

Jay R. Rueckl, Ph.D. Assistant Professor, Department of Psychology, Harvard University (collaborator on neural network models)

Olivier Koenig, Ph.D. Visiting Scholar (now returned to the University of Geneva)

Arlette Swift, Ed.D. Post doctoral fellow (neuropsychology)

## Ph.D. Degrees Awarded

C. B. Cave. The neuropsychology of navigation. Currently a post-doctoral fellow in Larry Squire's laboratory at UCSD.

M. Van Kleeck. Perceptual parsing in the cerebral hemispheres. Currently a post-doctoral fellow at M.I.T.

In addition, five graduate students work in the laboratory.

## Coupling Activies

### Presentations

Presentations were delivered at the following institutions. Unless noted otherwise, these were colloquia summarizing the material described in this Annual Report and were generally entitled "Components of High-Level Vision: A Cognitive Neuroscience Analysis"

Boston University
Princeton University
Massachusetts General Hospital (Behavioral Neurology rounds)
Longwood Medical Area (Harvard Medical School) Neurology grand rounds
Shattuck Hospital
Ohio State University
Brown University
University of Minnesota
University of Montreal
Massachusetts Neuropsychology Society
Washington University Medical School
Thinking Machines Corporation
Dartmouth University
University of Rochester
Cognitive Science Society Symposium on Cognitive Neuroscience of Attention
James S. McDonnell Summer Institute in Cognitive Neuroscience (Dartmouth University)
The Salk Institute
AFOSR Contractors' meeting in Alexandria, VA

### Honors

Federation of Social, Behavioral and Cognitive Sciences
Massachusetts Neuropsychology Society
Consultant, Naval Research Laboratories (19 January 1989)
Pew Memorial Trust Northeastern Neurosciences Program, grant preparation committee

National Research Council committee on Cognitive Psychophysiology
Symposium Co-organizer, 1989 meetings of Cognitive Science Society
Co-organizer, 1990 Cognitive Science Society meetings (to be held in Boston)
Editorial board: Journal of Cognitive Neuroscience (co-founder); Behavioral Neuroscience; Psychological Review; Journal of Visual Languages and Computing
External reviewer, programs in experimental psychology at Syracuse University.

## Patents and Copyrights

Harvard University is in the process of obtaining a copyright for the test battery.

## Additional Progress

The laboratory has also developed a general purpose neural network simulator, which appears to be more powerful than simulators that are commercially available. Two versions have been implemented, one for the Macintosh II and one for a UNIX VAX environment. In addition, a program called "quick stat" has been developed to compute statistics directly on the output from our tachistoscope simulator program for the Macintosh.

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